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Solar System Exploration Survey, 2013-2022

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Future Io Exploration for 2013-2022 and Beyond, Part 2: Recommendations for Missions

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Summary of Recommendations

The recommendations for future Io exploration as discussed in this white paper are summarized as follows:

1. *We recommend that NASA pursue a balanced solar system exploration program between life-focused and physical-science focused missions.*

2. *Although considerable Io observations will be planned by EJSM between 2025-2028, which we fully support, we recommend the next Decadal Survey support an 'Io Observer' mission of the Discovery-class or New Frontiers-class in the next decade.*

3. *We support the IVO mission, currently under study, as a candidate for a Discovery-class 'Io Observer' mission, consistent with previous Decadal Survey and current Io science goals*.

4. *We advocate for New Frontiers mission concepts for an 'Io Observer' mission later this decade, when RPS are again available for NF missions, consistent with previous Decadal Survey and current Io science goals*.

5. *We recommend that an Io orbiter be considered as a mission concept in the future, pending results from any jovi-centric 'Io Observers' operated during the 2020-2030 decade.*

6. *We recommend that* in situ *Io missions, perhaps penetrators, landers, or rovers, be considered as mission concepts in the future after 'Io Observer' missions.*

7. *We advocate for a new space-based UV telescope to study Io and other planetary targets in the 2013-2022 decade and beyond .*

8. *We recommend that NASA expand the time available for general planetary science on 8- to 10-meter class telescopes, by purchasing more time on existing facilities, or by constructing a dedicated large planetary telescope with nighttime AO capabilities.*

9. *We recommend that future NASA Io-observing space missions be accompanied by new support for ground-based monitoring programs that can enhance the spacecraft science return, e.g., by providing better temporal coverage of volcanic eruptions, for a small fraction of the mission cost.*

HOW WE CAN MAKE PROGRESS IN IO EXPLORATION

Though the search for life is one of the primary objectives of NASA's exploration, many of the major breakthroughs in our understanding of life's place in the universe have come from missions that were not primarily looking for life or organic chemistry; e.g., our understanding of the history and importance of planetary impacts derived from studies of our moon, the discovery of outflow channels on Mars by *Mariner 9*, the discovery of the importance of tidal heating by theoretical work and *Voyager 1* at Io, the discovery of circumstellar dusk disks by IRAS, and so on. Thus, *we urge that NASA pursue a balanced solar system exploration program between life-focused and physical-science focused missions.*

Io Missions for new starts in 2013-2022

Many of Io's primary science questions can only be answered by Jupiter- or Io-orbiting craft making high spatial- and spectral-resolution observations. From Earth's surface or even Earth orbit we are unlikely to achieve spatial resolution better than many tens of km, and we cannot make observations of Io's poles or night hemisphere or obtain the detailed compositional analysis possible without *in situ* observations. Earth-based observations also do not provide any information on the gravity and magnetic fields of Io, vital for internal structure studies. The magnetic field studies in particular are well suited to infer the presence of a magma ocean from electromagnetic induction response of Io. Previous missions that have encountered Io were not equipped with instruments designed to observe the then-unexpected volcanic processes taking place. Understanding the evolution of Io, and therefore the Jovian system, requires appropriate observations with a carefully crafted instrument payload designed to study the broad range of Io's volcanic activity.

Although Io orbiters have been proposed in the past, e.g., in the 1996 and 1999 Roadmap studies, the radiation hardness and delta-V issues that have emerged from studies of various Europa orbiter concepts (including the recent joint NASA-ESA Europa-Jupiter System Mission (EJSM) study) make an Io orbiter seem very difficult to accomplish with technology available in the decade of 2013-2022. Both the delta-V and radiation issues are even more severe at Io than at Europa. At the same time, Io's dynamism is not well suited to study from a one-shot flyby. The next mission to study Io in detail is thus likely to do so from Jovian orbit. Of course, a Jovi-centric orbit might also allow studies of the other Galilean satellites, and could resemble NASA's *Galileo* tour. However, a Jupiter-orbiting 'Io Observer' could accomplish much more for less cost due to advances in instrument capabilities and miniaturization over the 30 years since *Galileo* was designed, and the likely 100-fold improvement in data return possible with a functioning high-gain antenna. We therefore suggest the following strawman mission concept for an Io-dedicated mission (partially based on the recommendations of the Io White Paper [*Spencer et al*., 2002] prepared for the previous Planetary Science Decadal Survey [*Belton et al*., 2003].

> **Orbit:** Jovi-centric, eccentric, period roughly 1 month, perijove near Io. NASA should also explore endgame scenarios with shorter orbital periods and perhaps with only a few well-shielded instruments such as the telecom subsystem (for gravity data) and the magnetometer operational to provide a gravity and magnetic field survey of Io.

Duration: *Galileo* survived seven Io flybys, with a radiation dose of roughly 40 krad each. An inclined orbit reduces the dose per flyby to less than 20 krad. A four-year mission with 50 monthly Io flybys would accumulate less than a fourth of the 4 Mrad radiation dose expected for the Jupiter Europa Orbiter (JEO). Designing for a 1 Mrad total dose might not be possible within *New Frontiers* prior to the heritage gained from an EJSM mission. However, part of the spacecraft and its payload (such as the telecom system and the magnetometer) could be sufficiently shielded to achieve the gravity and magnetic fields objectives from repeated flybys of Io and if possible, Io orbit.

Payload: 1000-3000 Å UV spectrometer for atmospheric studies, with solar occultation capability; high-spatial resolution multicolor visible imager (1-10 m/pixel samples, 100 m/pixel global); 1-5 µm near-IR spectrometer with 1 km spatial resolution; 10, 20 µm thermal-IR imager with 10 km spatial resolution; laser altimeter; magnetometer for assessing permanent and induced fields from the interior of Io, mass spectrometer to analyze the composition of Io gases; plasma package to measure the amount and composition of the plasma picked up in Io's vicinity and the gravity experiment to measure static and time-dependent gravity fields. Possibly, a pair of penetrators with 20-hour lifetimes (comparable to DS2), each including a seismometer, atmospheric mass spectrometer, surface composition package, and possible ranging capability.

Orbiter Operations: Repeated flybys of the same hemisphere of Io, with similar lighting geometry, emphasizing studies of time variability. Active regions found early in the mission would become the focus of intensive repeated study in later flybys. Such flybys of the same hemisphere would also be ideal for electromagnetic induction studies requiring measurements of the time-variable inducing fields, shape-studies to understand the time-dependent flexing of Io and changes in Io's gravity fields from changes in its shape caused by tides. The remainder of the orbit would be used for both data playback and distant studies of Io and the Jovian system. NASA should explore endgames where Io orbit is achieved with only a few selected well-shielded instrument surviving to provide information on the permanent and variable gravity and magnetic fields.

Penetrator Operations: Penetrators would be released after impact sites had been chosen on early orbits, and will require retro-rockets to reduce impact speed. Mass spectrometers would determine atmospheric composition during entry, and surface composition could also be determined. Io is likely to be so seismically active that 20 hours of simultaneous coverage from three stations may be sufficient to map internal structure, though studies are needed to confirm this. Low-frequency seismometers would allow tidal flexing to be measured directly. This represents a huge technical challenge and needs much more study.

This strawman mission, an Io-dedicated, Jovian orbiter with penetrators, clearly falls within the *Flagship*-class (large) mission category. However, the next Outer Planets Flagship, the joint NASA-ESA Europa-Jupiter System Mission (EJSM), was selected in February 2009 for development in the 2013-2022 decade (ideal launch scheduled in 2020). Furthermore, a Titan-Saturn System Mission is a more likely candidate for the following Outer Planets Flagship in the 2023-2032 decade. *Although considerable Io observations are planned by EJSM between 2025-2028, which we fully support, we believe that a better goal for the next Decadal Survey is to support a more modest 'Io Observer' mission of the Discovery-class or New Frontiers-class in the next decade.*

In 2008, NASA requested mission proposals for a *Discovery*-class mission enhanced by two Advanced Stirling Radioisotope Thermoelectric Generators (ASRGs) provided as government-funded equipment. A candidate mission, called "Io Volcano Observer (IVO)", was proposed and is currently under study for the next *Discovery* opportunity (AO release expected in late 2009). The IVO mission concept is similar to that of the Io Strawman mission given above. It would include a single Jovian orbiter (JOI in 2021 or later) with 7 Io flybys over 16 months, with an extended mission option with additional Io flybys. Flybys would range from closest approach distances of ~1000 to 100 km, with ~20 Gb of science data near Io returned per flyby. The science payload would include, at a minimum, a Narrow-Angle Camera (10 ∝rad/pixel, 15 bandpasses from 200-1100 nm), a Thermal Mapper (125 μrad/pixel, 10 bandpasses for thermal mapping and silicate compositions), Ion and Neutral Mass Spectrometer (mass range 1-1000 amu/q, M/ΔM ranges from 300-1000), and two Fluxgate Magnetometers (sensitivity 0.01 nT). *We support the IVO mission as a candidate for a Discovery-class 'Io Observer' mission, consistent with previous Decadal Survey and current Io science goals*.

The 2008 NRC report "Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity" [*Bebe et al*., 2008] now supports an 'Io Observer' as a first-tier option for the NASA *New Frontiers*-class (medium-sized) missions during the next decade. Unfortunately, the 2009 *New Frontiers-3* Announcement of Opportunity (Release date: April 2009) does not include mission concepts including Radioisotope Power Systems (RPS). A solar-powered mission to Jupiter is feasible (e.g., *Juno*: *Bolton et al*. [2006]), but requires large solar arrays and hence a large spacecraft with enough fuel for capture into Jupiter orbit and has limited pointing ability. Note that sunlight is 27 times weaker at Jupiter (5.2 AU) than at 1 AU. Furthermore, telemetry of large volumes of data requires significant power. Although the top priorities of *Juno* can be accomplished with the return of only ~3 Gb of data [*Dodge et al*., 2008], meaningful Io exploration requires more than an order of magnitude more data. Gimbaled solar arrays would be required for an Io mission with the needed pointing capabilities, requiring still more power and creating a major challenge for pointing stability. Use of a RPS serves to greatly increase the science return and reduces the cost, mass, and risk of an Io mission. Nevertheless, future *New Frontiers* Announcements of Opportunity for later in the 2013-2022 decade are anticipated to include mission concepts with RPS. *Thus, we advocate for New Frontiers mission concepts for a 'Io Observer' mission beginning later this decade, consistent with previous Decadal Survey and current Io science goals*.

Missions for Beyond 2022

Whereas a Jovi-centric 'Io Observer' mission of either *Discovery*-class or *New Frontiers*-class could go a long way towards answering some of the questions posed above, an Io orbiter could accomplish even more. Laser altimetry from an Io orbiter would provide regional topographic information and lava flow thicknesses, but even from Jovicentric orbit it conceivably could measure tidal flexing. Such measurements should be attempted by the Jupiter Europa Orbiter (JEO) in the late 2020s. Repeated wide-area imaging at uniform illumination conditions and at consistent spatial resolution, multicolor photometry of plume dust, and laser altimetry would constrain resurfacing rates, and repeated detailed observations of active volcanic centers would reveal the true nature of Io's surface features, as well as eruption mechanisms. UV and mass

spectroscopic and solar occultation mapping would reveal the spatial distribution and dynamics of the atmosphere, and its sources and sinks. The gravity experiment would measure static gravity field to a degree and order of at least 10 to reveal the lateral variations in the interior mass distributions. The gravity experiment will also measure changes induced in the field by tidal deformations revealing the presence (or absence) of a magma ocean and/or distributed lava melts and characterizing the bulk properties of the lithosphere. The magnetic field experiment would characterize the permanent internal field to a degree and order of at least 10 to provide information on the metallic core of Io and the electromagnetically induced varying field at multiple frequencies, especially the rotation period of Jupiter and the orbital period of Io to infer the properties of a putative magma ocean. *Thus, we suggest that an Io orbiter be considered as a mission concept in the future, pending results from any future jovi-centric 'Io Observers'.*

Eventually, *in situ* measurements may be required to understand the full range of compositions and processes active on Io's surface and interior. For example, lander seismometers would reveal Io's interior structure, and by measuring the core size could distinguish between Fe and FeS core composition. Deploying landers with a surface composition package in Io's three types of plains material (yellow, white, and red-brown), and/or in the dark diffuse material or on Io's dark and bright flow materials, would unambiguously reveal the compositions of Io's eruptive products, provide *in situ* temperature measurements, and consequently lead to constraints on internal processes. Alternatively, it may be more cost effective to deploy a rover rather than 3-4 landers, at a location where all of Io's various surface materials are in close proximity. Continued technology developments in RPS, radiation-hardening, and communications over the next 15 years suggest that active Io *in situ* equipment could become a reality. *Thus, we recommend that* in situ *Io missions, perhaps penetrators, landers, or rovers, be considered as mission concepts in the future after 'Io Observer' missions.*

Space-Based Telescopes

Space-based telescopes provide a critical capability that is largely complementary to both ground-based telescopes and *in situ* spacecraft observations. Fundamental contributions to our understanding of both the Io atmosphere, and its interaction with the plasma torus, have been made by several space-based facilities in the past 20 years. For example, discovery of the atomic sulfur and oxygen emissions at Io, which are a basic diagnostic of the plasma interaction with the satellite, was made using the *International Ultraviolet Explorer* (IUE) satellite in 1986. Observations with the *Hubble* Space Telescope (HST) have provided the only quantitative spatially resolved information about Io's SO_2 atmosphere, and determined to first order its basic spatial distribution. HST and ground-based telescopes have also provided the spectroscopic observations of volcanic plumes; in particular, HST discovered molecular sulfur (S_2) in the Pele plume. The UV imaging capability of HST has provided detailed information about the plasma interaction with the satellite via its images of the atomic emission morphology, which provides basic ground truth for the detailed magnetohydrodynamic models of the interaction. *Extreme Ultraviolet Explorer* (EUVE) observations of the Io torus discovered Na^+ emission. None of the spacecraft sent to the Jovian system (*Pioneer, Voyager, Galileo, Cassini, New Horizons*) has had the ability to make these measurements.

Generally speaking, the space-based capability that has proven most useful for studying Io and its plasma torus is access to the ultraviolet portion of the electromagnetic spectrum. There are two reasons for this: 1) SO_2 and other atmospheric molecules have strong absorption bands throughout the UV spectral region; and 2) the electronic ground state transitions of both sulfur and oxygen occur in the ultraviolet. Additionally, the Io plasma torus radiates primarily at UV wavelengths. A UV capability combined with the superior spatial resolution and small spectroscopic slits on HST instruments have provided the most comprehensive results compared with other more specialized facilities such as EUVE or *Far Ultraviolet Spectroscopic Explorer* (FUSE). It is therefore of very high priority for continued success in unraveling Io's secrets to strongly endorse a widely accessible successor to HST with UV capability. An obvious next step would be to have diffraction-limited capability in the UV, which HST lacks, and UV detectors with higher quantum efficiency than HST's. The *James Webb* Space Telescope's lack of UV capability, its tailoring to astrophysical, and particularly cosmological, problems, and its lack of planetary capability (specifically, the ability to track moving targets) will give it only limited usefulness for Io observations. Thus, *we advocate for a space-based UV telescope with diffraction-limited capability to study Io and other planetary targets.*

A second important capability that is dearly needed for progress in Io studies is a long-term synoptic monitoring capability in space-based facilities. Observations such as the ones described above have given us only the shortest glimpse (e.g., the science time available in one HST orbit is only about 40 minutes) at the true nature of Io's atmosphere and torus interaction. While the first order spatial structure of Io's SO_2 atmosphere is now known, these observations also make it obvious that, as expected, the atmosphere is highly variable. What they are unable to untangle, due to the general scarcity of the observations, is how much of the variability is due to actual physical causes (e.g., the volcanoes) and how much is due to factors due only to the viewing geometry (such as correlation with specific features on Io's surface). Space-based facilities such as HST that provide only a brief, in-depth snapshot will never be capable of telling the full story. A facility that provides long term synoptic monitoring capability, such as the previously proposed JMEX (*Jupiter Magnetospheric Explorer*) or JIST (*Jovian Imaging and Spectroscopic Telescope*) missions, or the more general-purpose SCOPE (cross-Scale COupling in Plasma universE) proposal, provides the best hope of allowing us to explain the complex, and intricately interconnected, Io-torus-magnetosphere system. A Jupiter-orbiting space telescope, orbiting at (for example) Ganymede's orbit, equipped with a 0.5-1.5 meter, MIDAS-like (Multiple Instrument Distributed Aperture Sensor) optical system, would also provide excellent ability to monitor Io, as well as Jupiter's atmosphere, rings, and other satellites. Alternatively, if funding limitations inhibit development of these space-based missions, then distant Io observations by planetary spacecraft cruising through the Jovian system for extended periods (e.g., JEO will perform a 30-month Jovian system tour with distant Io monitoring) could provide similar data. Thus, *we advocate for space-based missions that enable long-term (years) monitoring of Io over a range of time scales (seconds, minutes, hours, days, months, years), and spatial and spectral resolutions.* We support these type of Io observations that may be obtained by the EJSM.

Ground-Based Telescopes

Many Io phenomena, such as thermal emission from its volcanoes, emissions from its atmosphere and torus, its reflectance spectrum, and even its large-scale albedo patterns, can be

studied from the Earth's surface, providing the cheapest way to study Io's time variability. Io's dynamism requires frequent observations to capture and understand the full range of phenomena that it exhibits; for instance, the largest infrared volcanic "outbursts" are seen only a few percent of the time. Such monitoring is most easily done on smaller telescopes like the *InfraRed Telescope Facility* (IRTF) that have limited spatial resolution, but queue scheduling can allow frequent snapshots even on heavily subscribed large 8- to 10-meter-class telescopes. Multi-wavelength infrared observations of the volcanic thermal emission can constrain magma temperatures, eruption mechanisms, spatial distributions, and the time evolution of these quantities. Over the last decade, advances in adaptive optics (AO) with large telescopes providing 20 or more pixels across Io's disk have opened a new and exciting field of ground-based disk-resolved studies. New instrumentation also enables new observational possibilities: e.g., high-spectral-resolution 7-8 micron spectroscopy of Io, coupled with AO on a 30-meter-class telescope, which could directly map the SO_2 atmospheric distribution and characterize its temporal variability.

Thus, we recommend that NASA expand the time available for general planetary science on 8- to 10-meter class telescopes, by purchasing more time on existing facilities, or by constructing a dedicated large planetary telescope with nighttime AO capabilities. Creative scheduling, including queue-scheduled, remote, service, and daytime (non-AO) IR observing, can maximize the efficiency of these expensive facilities, particularly for bright objects like Io where integration times are often short. Continued support for smaller facilities that can do crucial temporal studies is also important. Telescope time on "smaller" facilities may become available as these are replaced by the next generation of giant telescopes: for instance Caltech time on the Palomar 5-meter might be available for purchase by NASA if the Thirty Meter Telescope (TMT) is built. *Furthermore, we recommend that future NASA Io-dedicated space missions should include in their budgets support for ground-based monitoring programs that can enhance the spacecraft science return, e.g., by providing better temporal coverage of volcanic eruptions, for a small fraction of the mission cost.*

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